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SPECTRUM AND OCTAVE BAND ANALYSIS OF PRESSURE PULSES FROM DEEP UNDERWATER EXPLOSIONS

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SPECTRUM AND OCTAVE BAND ANALYSIS OF PRESSURE PULSES FROM DEEP UNDERWATER EXPLOSIONS

by

Mary Alice Genau

ABSTRACT: Fourier spectra were computed on the IBM 7090 for analog tape recorded pressure pulses of underwater explosions fired at sea in February 1965. Depths ranged from 500 to 14,000 feet; charges weighed 1 to 88 pounds; the compositions fired were TNT, pentolite, HBX-3, and Nitramex. Reduced spectra of charges weighing up to 57 pounds agreed with previous results from 1 and 10 pound charges at the same depths. Only slight differences due to composition were found.

UNDERWATER EXPLOSIONS DIVISION
EXPLOSIONS RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
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SPECTRUM AND OCTAVE BAND ANALYSIS OF PRESSURE PULSES FROM DEEP UNDERWATER EXPLOSIONS

The work reported here is an extension and continuation of studies on the frequency spectra of explosions in the ocean. It was carried out under Task NOL-785 for the Advanced Research Projects Agency.

Mention of commercially available instruments or materials does not constitute an endorsement by the Laboratory.

E. F. SCHREITER
Captain, USN
Commander

C. J. ARONSON
By Direction

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SPECTRUM AND OCTAVE BAND ANALYSIS OF PRESSURE PULSES FROM DEEP UNDERWATER EXPLOSIONS

1. INTRODUCTION

Weston (reference a)* derived an analytical approximation of a frequency spectrum analysis which is applicable to the pressure pulse near a relatively shallow underwater explosion. In order to determine the effect of depth upon the spectrum, Christian and Blaik (reference b) performed a spectrum analysis in 1964 on data obtained earlier by several different investigators. The data they used, which was all recorded near the surface, was from 1- to 10-lb charges fired at depths between 7000 feet and 22,000 feet.

To extend the range of depths to shallower conditions, and to include larger charges, a series of shots was fired at sea in 1965. The experimental conditions for these shots are given in Table 1; for comparison, the conditions for the earlier experiments are also shown. This paper reports the results of the frequency spectral analyses performed on the 1965 shots.

2. EXPERIMENTAL CONDITIONS

The experiments were carried out in February 1965 about 200 miles east of Eleuthera, in water about 18,000 feet deep. The gage for recording the pressure pulses was suspended from the USNS GILLIS at a depth of about 200 feet. The charges were fired at depths ranging from approximately 500 to 14,000 feet directly beneath the ship.

One Atlantic Research Corp. Type LC-32 hydrophone was used to pick up the pressure pulses. The same gage output was recorded on two oscilloscope channels, using different gains and sweep speeds. Almost immediate observation of pressure-time data was obtained from Polaroid prints. FM magnetic tape recordings were also obtained from the same gage at 60 inches per second on the FR-600 tape recorder. The frequency response of the FM recorder was essentially flat from 0-20 kcs; the hydrophone, however, gave some low frequency distortion (reference c).

Most of the charges fired were TNT and HBX-3; 1-lb, 8-lb, and 55-lb charges were used. In addition, some 1-lb pentolite and 88-lb Nitramex** charges were used. Attempts to fire 1000-lb TNT charges failed (reference d). All charges were boostered with pentolite which in turn was initiated with hydrostatic firing devices which were set for nominal depths of 500, 800, 1200, 3000, 4500, 7000, 10,000, and 14,000 feet.

* References are listed on page 8.

** Manufactured by E. I. Dupont de Nemours & Co. The composition is 16% TNT/4% DNT/30% $NaNO_3$/35% NH_4NO_3 plus iron and phosphorus.

The shot data are given in Table 2.

3. DATA ANALYSIS

3.1 Method of Data Reduction. The analog tape data was digitized by the Mathematics Department of the David Taylor Model Basin on their Computer Data Format Translator (CDFT), which has a capability of sampling 2000 times per second. The analog tapes were played back on the DTMB Ampex FR-600 at 3-3/4 inches per second and sampled and digitized 1875 times per second on the CDFT. Since the data was recorded at 60 inches per second, this is equivalent to sampling at 33 microsecond intervals in real time. The sampling should have been performed at 25 microsecond intervals in order to observe the Nyquist criterion of sampling 20 kc data. However, sampling at the next lower playback speed of 1-7/8 inches per second resulted in too much noise and so was not done.

A fiducial marker one millisecond ahead of the pressure pulse on the analog tape initiated digitizing by the Compter Data Format Translator. The 1-millisecond baseline was digitized so that the average value of the baseline could be obtained. The sampling rate was sufficient to average out the dominant high frequency noise; however, the baseline was too short to average out the inherent 60 cycle noise.

The number of times a pulse was sampled ranged from about 500 samples for the deep shots to 5000 samples for the shallow shots. The digitized tapes were the input to the IBM 7090 computer program, NEWGRL, described in reference (e).

3.2 Types of Analysis Performed. Three types of computation were carried out on the IBM 7090 computer. These were:

(1) The energy spectral density E(f)* of the positive phase of the shock wave only was computed as described in reference (e). The energy spectral density was computed in increments of 50 cps from 50 cps to 16 kcs, and the points were connected by straight lines by the CAL COMP 565 plotter.

(2) The spectrum was similarly computed for the pressure pulse through several pressure oscillations until the pressure returned to the noise level. The frequency interval at which the spectrum was computed was smaller than 50 cps to better define the spectrum for shallow shots which have long bubble periods. In all cases, the integration was carried out to the end of the positive phase of the last bubble pulse observed on the tape records. The number of bubbles integrated is given for each shot in Table 2.

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* $E(f) = \frac{2}{\rho c}|A(f)|^2$ where A(f) is the amplitude spectrum described in reference (e) and $\rho c = 1.506 \times 10^5$.

(3) The energy in octave bands from low frequencies up through the 8-16 kcs band was also computed on the IBM 7090 for both cases--the shock wave alone and with several pulses. The lower octave band energies were included since it was of interest to determine the rate at which the energy decreased with decreasing frequency for frequencies less than the bubble period frequency.

3.3 Accuracy of DTMB Computer Data Format Translator. Since the CDFT had not been used previously for analyses of explosion pulses, several checks were run. In one instance, the same record was digitized twice on different days.

The agreement between pairs of frequency spectra was found to be quite good at low and mid-frequencies, except that even slight shifts in the baseline affected the lowest frequencies noticeably. At the highest frequencies, differences were found in the slopes of the spectral density curves; these were attributed to the sampling rate which was not fast enough in this region.

This matter is discussed in more detail in Appendix A.

In addition, an analysis of the oscilloscope data for a few shots was made in order to obtain an overall check of the spectrum results digitized by the CDFT. Data reduction of the oscilloscope records was done as outlined in section 4 of reference (e). The two methods gave good agreement.

4. ENERGY SPECTRUM OF THE TOTAL PULSE

4.1 Effect of Number of Bubbles Integrated. Figure 1 shows two spectra computed from the same digital tape. In one case the computation was stopped at the end of the positive phase of the first bubble pulse, and in the other the computation was stopped after the third bubble pulse.

There appear to be two effects attributable to the difference in integration time. First, the maximum energy shifts to higher frequencies for the integration through the larger number of bubble pulses. Second, the spectrum computed through one bubble pulse is smoother than that through three, where the second and third oscillations are somewhat distorted. Both effects are due to the fact that the bubble pulse amplitudes and periods decrease with successive pulses.

4.2 Effect of Charge Weight. To examine the effect of charge weight on the spectrum, a comparison is made in Figure 2 among the spectra of three TNT charges fired at nearly 4400 feet and weighing 1, 8, and 57 pounds. The 1- and 57-pound shots were integrated through three bubbles and the 8-lb shot was integrated through two bubbles.

In Figure 2 the energy level has been reduced by the factor (weight$^{4/3}$) after Weston (reference a), and the frequency has been reduced by multiplying

by $(\text{weight}^{1/3})$. It is observed that these reduction factors result in good agreement among spectra of varying charge weight ranging from 1 to 57 pounds where the charge composition and burst depth are the same.

4.3 Effect of Range-Depth. Since the shots were recorded near the surface, the effects of burst depth and propagation distance upon the spectra are difficult to separate (reference b). The effect of depth-range upon the spectrum is illustrated in Figure 3 in which a plot of the spectra of three 1-lb HBX-3 charges where the vertical charge-to-gage range, R_v, is equal to 1154 feet, 4335 feet, and 9637 feet respectively.

In Figure 3 the energy level has been reduced by R^{-2}, a spherical spreading factor. The spectra are affected by depth, as expected. The low frequency differences are caused by the effect of depth on the bubble period; the maximum energy is at a frequency proportional to $z_o^{5/6}$, where z_o is the hydrostatic depth. The apparent attenuation of higher frequencies with range may or may not be real; resolution of this question requires further analysis of these data.

4.4 Effect of Charge Composition. In Figure 4, three one-lb charges of different compositions fired at a vertical range of about 1150 feet are compared. The relatively flat slope of -4.5 dB for HBX-3 in the 7-16 kcs band is probably an artifact caused by the sampling rate discussed previously (Section 3.3 and Appendix A). The slopes of the other two spectra are -9 dB and -10 dB per octave for TNT and pentolite, respectively. The TNT and pentolite spectra appear to agree rather well. In contrast the HBX-3 spectrum has two differences:

(1) The maximum peak and corresponding peaks have shifted to lower frequencies because of the longer first bubble period.

(2) The amplitude of oscillation of the spectrum for HBX-3 is not so great as for TNT or pentolite. This is attributed to bubble pulse pressures damping out at a faster rate than those of TNT and pentolite.

The slopes of the three spectra are similar at frequencies below the bubble period frequency.

Figure 5 shows the maximum energy spectral density reduced by $W^{4/3}$ plotted versus vertical range for all the 1965 data. The scatter in the data is such that no statistically significant conclusions can be drawn. However, the HBX-3 points would average perhaps 2 dB higher than the TNT points. The TNT points average about 2 dB lower than those reported by Christian and Blaik (reference b) for TNT and pentolite combined. Finally, the Nitramex data appear to be the lowest.

5. OCTAVE BAND ANALYSIS

Using Simpson's Rule, the energy in ten octave bands starting with the 15-30 cps band and including the 8-16 kcs band was computed on the

IBM 7090 computer for all the 1965 shots. This analysis was performed for the positive phase of the shock wave (except for the lowest bands) and also for the pulse including several bubbles, and is presented in Tables 3 and 4, respectively.

5.1 Octave Band Energy for the Shock Wave. Figure 6 is a plot of octave band energy of the positive phase of the shock wave for four HBX-3 charges, weighing from 1 to 50 pounds and fired at a vertical range of about 4200 feet. The experimental energy level was reduced by multiplying by the weight factor, $W^{4/3}$, and multiplied by the spherical spreading term relative to 100 yards, $[R(yds)/100]^2$. Also, the frequency was multiplied by the factor (weight$^{1/3}$). This results in the energy spectrum level for a 1-lb charge at 100 yards range.

The next four plots (Figures 7-10) present the shock wave octave band energy of all the 1965 data, for TNT, HBX-3, pentolite, and Nitramex, respectively. The octave band energies and the frequency were reduced by the same factors as in Figure 6, and each curve was obtained by drawing by eye an average line through the data for each of the nominal ranges. In general, the scatter about each of the curves drawn is about the same as that shown in Figure 6. However, for certain depths* the relatively few data points and the scatter of the data in the 8-16 kcs band resulted in curves which are not reliable in the high frequency region.

At the very low frequency end of the spectrum, the energy level approaches the shock wave impulse. In this region, the energy decreases with increasing depth and this is characteristic of all data. This is expected since the shock wave impulse decreases faster than range^{-1} (reference f) for all compositions. The spread in the reduced spectra decreases with increasing frequency until a minimum is obtained at about 2000 cps x lbs$^{1/3}$. As the frequency increases further, the spread in energies increases again; the energy in general decreases with increasing depth as occurred at the low frequencies.

The change in the shock wave spectra at the low frequency end as the depth is varied is a consequence of the change in the waveform with depth. As the depth increases, the shock wave duration decreases, resulting in a shorter pulse which will produce less energy in the lower frequencies.

The HBX-3 spectra show 1 to 3 dB higher energy than TNT at the lowest frequencies for all ranges. Since the spectrum approaches the impulse at zero frequency, this higher energy level for HBX-3 is caused by higher shock wave impulse (reference f). In general, the TNT and HBX-3 data are in good agreement at all but the lowest frequencies. Pentolite is 1 dB to 3 dB higher than TNT for all frequencies at the three ranges for which data exist. Nitramex is 2 dB or 3 dB lower than TNT at most frequencies for corresponding depths. Nitramex has a slope of -6 dB per octave in the high frequencies; this is a relatively high slope.

* TNT data at nominal depths of 1200 ft and 4500 ft; HBX-3 data at nominal depths of 1200, 2000, 4500, and 10,000 ft; Nitramex data at the nominal depth of 3000 ft.

There are two slight anomalies in the HBX-3 data: the 2000 ft data are consistently 1 or 2 dB higher than the 1200 ft data, and the energies for the one 3000 ft depth shot fired are higher than the 1200 ft depth energies. Again these comparisons are based on statistically inadequate data.

5.2 Octave Band Energy for the Total Pulse. The next four plots (Figures 11-14) show the octave band energy for the total pulse (shock wave plus one or more bubble pulses as indicated in Table 2) for the four compositions. Again the energy level is reduced by weight$^{4/3}$ and multiplied by the spherical spreading factor; the frequency is reduced by weight$^{1/3}$ as in Figures 7-10. The octave band energy density points were connected by straight lines and the maximum value is an extrapolation of these curves at the bubble period frequency.

It is observed in the four sets of data that there is no systematic change in the slope of the line for frequencies less than the bubble period frequency. An accurate determination of the slopes for these frequencies could not be made since in general there were only two octave bands below the bubble period frequency. Furthermore, the difficulty in determining the value of the baseline (discussed in Section 3.1) may have resulted in large variations of energy for the lowest bands. However, the curve in this region usually has a steeper slope (8 dB or 9 dB per octave) than the slope of 3 dB or 4 dB per octave reported by Christian and Blaik (reference b), and is believed to be more realistic, since it is based on considerably more data and a more closely spaced frequency analysis.

In comparing the data for different charge compositions at the same ranges, it was observed that TNT and HBX-3 have comparable energy levels for reduced frequencies greater than 1 kc$\cdot$W$^{1/3}$. However in the low frequency region, the maximum energy for HBX-3 is greater than that for TNT and occurs at lower frequencies. Pentolite has a 2 dB to 4 dB higher energy level than TNT for most frequencies. It must be noted that there is only one pentolite shot and only one weight--1 pound--at each of the three ranges. Nitramex was observed to have a 2 dB to 4 dB lower energy level than TNT for all frequencies; this, too is based on scanty data.

6. CONCLUSIONS

(1) The good agreement previously found between the reduced total pulse energy spectra of 1- and 10-pound charges has been shown to hold up to 57-pound charges.

(2) The total pulse energy spectra of charges fired at various vertical ranges between 500 and 14,000 feet vary with depth as expected from previous work.

(3) The total pulse energy spectra of TNT and pentolite are almost identical; the HBX-3 spectrum shows a maximum (and succeeding peaks) at a

lower frequency, less oscillation, and smaller attenuation at the highest frequencies. The energy of the maximum was not statistically different for the four compositions fired; however, HBX-3 gave the highest values and Nitramex the lowest.

(4) The octave-band energy for the shock wave alone and for the total pulse show the effect of depth in sharpening the shock waveform and decreasing the bubble period. The low frequency drop off of 8-9 dB per octave for the total pulse energy is believed to be a better value than the previous one.

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(c) J. P. Slifko, "Evaluation of Hydrophones for Underwater Explosion Pressure Measurements", NOL internal report TN 7107, 5 Jan 1966.

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(e) M. A. Genau, "Underwater Shock Wave Frequency Spectrum Analysis IV. Fortran IV Programs for the IBM 7090 Computer", NOLTR 66-3, Feb 1966.

(f) M. Blaik and E. A. Christian, "Near-Surface Measurements of Deep Explosions I. Pressure Pulses from Small Charges", J. Acoust. Soc. Am. 38, 50-56 (1965).

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TABLE 1

COMPARISON OF PREVIOUS AND CURRENT EXPERIMENTAL CONDITIONS

	Christian and Blaik (reference b)	February 1965 Sea Trials
Charge Weight	0.4 to 10 lbs	1 to 88 lbs
Charge Depth	7000-22,000 ft	500-14,000 ft
Charge Composition	TNT, Pentolite	TNT, Pentolite, HBX-3, Nitramex
Position of Recording Gages	Vertically above charge near surface	Vertically above charge near surface
Pulse Sampling Method	Pressures sampled at discrete time intervals from paper and film records	Pressures from analog tape data electronically sampled and digitized using Computer Data Format Translator
Length of Pulse Analyzed	To minimum pressure or end of negative phase after second bubble pulse	To end of positive phase of last observable bubble pulse
Lowest Octave Band	250-500 cps	15-30 cps

TABLE 2

SHOT STATISTICS

Charge Weight (lb)	Charge Composition	Nominal Depth (ft)	Burst Depth (ft)	Shot Number	Number of Bubble Pulses Included In Spectrum Computation
1	TNT	500	517	22	1
		500	575	48	2
		500	607	33	1
		800	873	49	2
		800	893	67	2
		1,200	1,158	42	3
		1,200	1,241	70	2
		2,000	1,983	27	3
		3,000	2,963	45	3
		3,000	3,032*	10	3
		4,500	4,411	24	3
		4,500	4,502*	52	3
		7,000	7,402*	77	3
1	PENTOLITE	500	552	64	3
		1,200	1,377	68	2
		7,000	6,621*	5	3
1	HBX-3	1,200	1,331	46	3
		2,000	1,891	65	4
		4,500	4,228*	51	3
		4,500	4,517	56	3
		10,000	9,824	73	4
8	TNT	500	430	26	1
		500	571	31	1
		800	892	12	1
		1,200	1,139	72	3
		1,200	1,237	43	2
		1,200	1,250	69	2
		2,000	1,871	21	3
		2,000	2,031	35	3
		2,000	2,051*	4	2
		3,000	2,924	47	3
		4,500	4,305	32	3
		4,500	4,372	25	2
		4,500	4,542	55	3
		14,000	13,300*	18	3
		14,000	13,400	36	3
8	HBX-3	1,200	1,182	44	3
		1,200	1,358	11	2
		4,500	4,202	50	2
		10,000	9,849	71	3
		14,000	13,540*	75	3

* Depth determined from bubble period.

TABLE 2

SHOT STATISTICS (cont'd)

Charge Weight (lb)	Charge Composition	Nominal Depth (ft)	Burst Depth (ft)	Shot Number	Number of Bubble Pulses Included In Spectrum Computation
57	TNT	2,000	1,844	8	2
		2,000	1,923	29	2
		4,500	4,282	37	2
		4,500	4,413	20	3
		7,000	6,608*	3	3
		7,000	7,147*	79	3
		14,000	14,340	62	3
50	HBX-3	2,000	1,813	63	2
		3,000	2,891	78	3
		4,500	4,443	53	2
		7,000	7,498	57	3
		10,000	9,547	59	2
88	NITRAMEX	3,000	2,793	38	2
		3,000	2,900	19	1
		7,000	7,051	39	3
		10,000	10,308	40	3

TABLE 3

SHOCK WAVE SPECTRUM
Octave Band Energies (ergs/cm^2)

1-lb TNT

Shot No.	Range (ft)	Octave Bands 60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
22	337	254.3	268.3	292.3	312.1	320.1	262.0	110.6	42.73
48	397	113.9	145.5	169.5	237.2	214.9	180.7	101.6	41.50
33	426	127.2	155.7	203.8	274.4	226.7	210.7	108.1	64.42
49	694	29.01	46.74	58.60	71.23	67.28	56.67	32.52	20.05
67	705	32.16	54.16	74.68	75.60	91.14	75.63	46.74	30.37
42	978	12.81	21.91	31.03	38.15	35.72	28.19	15.82	8.149
70	1,059	11.42	20.15	30.17	35.10	35.63	19.99	11.84	2.423
27	1,806	2.986	5.526	9.571	12.03	11.62	9.525	5.137	2.733
45	2,782	0.7330	1.377	2.519	3.702	3.891	2.729	1.157	0.2811
10	2,850	0.7659	1.437	2.611	3.674	3.191	2.364	1.194	0.5183
24	4,244	0.5972	2.185	2.244	2.051	1.862	1.350	0.6679	0.3866
52	4,322	0.2604	0.4961	0.9567	1.661	2.041	1.605	1.003	0.7627
77	7,222	0.07285	0.1390	0.2699	0.4795	0.6162	0.3864	0.1846	0.07060

TABLE 3

SHOCK WAVE SPECTRUM (continued)

1-lb Pentolite

Shot No.	Range (ft)	Octave Bands 60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
64	367	320.8	331.0	429.5	528.4	493.2	382.8	225.0	140.2
68	1,191	11.19	20.17	32.33	32.22	34.04	24.75	11.16	2.039
5	6,441	0.1426	0.2716	0.5234	0.9055	1.072	0.6494	0.3142	0.1039

1-lb HBX-3

Shot No.	Range (ft)	60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
46	1,154	11.12	19.36	28.38	28.21	25.55	17.72	9.596	3.267
65	1,705	5.789	10.31	15.73	16.45	14.31	9.484	4.188	0.7816
51	4,048	0.4218	0.7966	1.485	2.276	2.135	1.529	1.020	0.7547
56	4,336	0.3632	0.6860	1.280	1.968	1.805	1.057	0.4586	0.08841
73	9,637	0.05319	0.1015	0.1966	0.3463	0.4251	0.2193	0.09335	0.01492

8-lb TNT

Shot No.	Range (ft)	60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
26	249	2252.	2781.	2833.	3031.	2133.	1366.	712.4	394.8
31	384	2288.	2327.	2712.	3433.	2259.	1464.	578.6	153.6
12	715	472.3	576.7	602.7	629.9	436.7	274.6	163.7	111.5
72	951	273.8	377.8	417.7	390.1	322.6	184.5	83.74	32.35

TABLE 3

SHOCK WAVE SPECTRUM (continued)

8-lb TNT

Shot No.	Range (ft)	Octave Bands 60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
43	1,059	201.2	270.1	296.7	324.9	275.9	150.0	90.39	73.63
69	1,067	198.7	292.9	306.7	299.1	254.7	142.6	83.61	45.60
21	1,701	56.84	92.39	112.8	107.7	90.66	43.23	18.04	6.129
35	1,854	37.16	62.51	80.35	86.04	76.15	38.16	18.77	8.592
4	1,871	48.77	79.68	97.00	101.3	69.12	36.75	18.06	7.866
47	2,743	13.18	23.49	35.76	36.85	30.81	14.03	6.036	1.524
32	4,130	4.598	8.445	14.19	15.77	10.96	5.241	2.098	0.6312
25	4,200	5.266	9.616	15.79	16.32	10.78	5.086	1.985	0.3738
55	4,362	5.359	9.788	16.08	16.50	9.930	5.034	2.450	1.155
18	13,119	0.2072	0.3900	0.7184	1.044	0.7329	0.2605	0.1154	0.03576
36	13,222	0.2455	0.4652	0.8786	1.401	1.208	0.4037	0.1716	0.05183

8-lb HBX-3

Shot No.	Range (ft)	60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
44	1,000	309.0	328.6	359.0	343.3	264.4	153.6	92.49	67.66
11	1,178	172.0	207.0	220.9	201.6	176.3	88.13	41.93	8.121
50	4,022	7.294	12.79	18.32	15.88	12.14	5.552	2.615	1.081
71	9,665	0.8808	1.636	2.857	3.465	2.118	1.049	0.5494	0.2666
75	13,360	0.3539	0.6618	1.187	1.556	0.8795	0.4448	0.1815	0.05193

TABLE 3

SHOCK WAVE SPECTRUM (continued)

57-lb TNT

Shot No.	Range (ft)	Octave Band 60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
8	1,660	751.0	831.9	847.8	736.4	360.4	183.9	82.84	30.27
29	1,744	609.2	680.8	704.8	553.2	405.7	189.0	88.03	37.28
37	4,102	72.27	111.7	113.7	77.97	43.34	20.67	7.918	1.336
20	4,251	65.02	106.0	120.9	81.86	48.61	22.62	10.40	4.765
3	6,428	17.14	30.23	43.42	29.02	13.80	7.376	3.553	1.296
79	6,967	20.13	34.86	47.29	32.00	15.55	7.207	4.182	2.532
62	14,162	2.778	5.020	7.895	6.765	3.173	1.333	0.7216	0.4124

50-lb HBX-3

Shot No.	Range (ft)	60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
63	1,626	1246.	1066.	1038.	703.4	479.6	200.0	103.2	30.46
78	2,760	302.2	373.1	323.8	251.1	147.2	73.81	48.23	36.76
53	4,259	96.83	133.3	121.8	93.32	46.58	22.07	13.55	8.560
57	7,326	17.76	29.56	34.49	17.82	10.75	5.039	2.607	1.283
59	9,419	4.428	7.694	10.46	6.415	3.562	1.606	0.7515	0.3440

TABLE 3

SHOCK WAVE SPECTRUM (continued)

88-lb Nitramex

Shot No.	Range (ft)	Octave Bands 60-125	125-250	250-500	500-1000	1-2kc	2-4	4-8	8-16kcs
38	2,610	314.0	357.9	314.4	231.3	138.1	68.41	41.72	22.05
19	2,751	220.1	275.0	230.9	164.3	83.97	44.03	22.29	11.53
39	6,864	15.37	25.65	31.34	21.82	10.54	5.340	3.036	1.829
40	10,122	5.577	9.850	14.21	9.577	4.607	2.609	1.503	1.077

TABLE 4

SPECTRA OF PULSE INCLUDING SEVERAL BUBBLES
Octave Band Energies (ergs/cm^2)

1-lb TNT

Shot No.	Range (ft)	Octave Bands 15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
22	337	70.73	597.9	444.8	492.7	471.7	618.7	377.8	240.8	127.1	50.46
48	397	29.47	313.1	335.6	298.8	290.9	311.8	192.6	176.9	103.4	80.59
33	426	14.88	362.7	319.8	262.8	347.8	400.1	255.4	208.9	113.0	68.05
49	694	3.534	36.54	155.0	108.3	110.7	101.9	70.28	48.74	22.47	6.783
67	705	4.238	46.54	209.3	149.3	141.4	120.6	103.3	79.84	18.98	31.13
42	978	1.531	10.69	88.72	53.18	58.54	54.48	38.71	28.15	16.35	9.208
70	1,059	0.8263	9.404	94.46	49.97	65.27	50.74	39.25	21.81	12.42	2.490
27	1,806	--	0.3819	12.72	33.78	20.37	19.45	13.15	9.696	5.229	2.791
45	2,782	--	0.1640	1.502	11.67	7.031	6.538	4.666	2.838	1.188	0.3023
10	2,850	--	0.04314	1.005	11.84	6.928	7.138	3.474	2.518	1.221	0.5411
24	4,244	--	--	0.2017	3.016	6.096	3.312	2.446	1.457	0.6876	0.3957
52	4,322	--	--	0.2080	2.709	6.028	3.369	2.862	1.712	1.009	0.7766
77	7,222	--	--	0.01588	0.1795	2.410	1.279	0.7812	0.4141	0.1953	0.07955

TABLE 4

SPECTRA OF PULSE INCLUDING SEVERAL BUBBLES (continued)

1-lb Pentolite

Shot No.	Range (ft)	Octave Bands 15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
64	367	35.35	862.1	621.1	818.6	651.6	772.0	579.9	385.1	236.2	154.4
68	1,191	0.4993	7.270	92.01	56.69	67.58	50.84	43.38	26.66	11.66	2.750
5	6,441	--	--	0.04316	0.5254	4.574	2.614	1.722	0.7499	0.3236	0.1114

1-lb HBX-3

Shot No.	Range (ft)	15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
46	1,154	1.332	13.65	84.59	62.69	41.87	40.15	27.86	20.49	14.09	9.571
65	1,705	--	2.213	44.04	40.41	24.34	19.69	14.17	9.679	4.394	0.8385
51	4,048	--	--	0.4638	6.8	5.082	2.487	2.273	1.505	1.034	0.7620
56	4,336	--	--	0.3124	5.860	4.831	2.262	1.806	1.071	0.4591	0.09497
73	9,637	--	--	0.009145	0.1022	1.643	0.7860	0.3927	0.2255	0.09197	0.01570

8-lb TNT

Shot No.	Range (ft)	15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
26	249	4749.	6262.	4216.	3798.	3781.	3603.	2026.	1400.	800.	407.9
31	384	5450.	5252.	4407.	3443.	3443.	4413.	2345.	1321.	631.2	195.0
12	715	343.1	1079.	1151.	841.4	804.3	1002.	473.4	302.4	166.9	102.0
72	951	106.1	994.4	771.1	653.5	587.2	451.3	324.4	184.9	83.48	35.59

TABLE 4

SPECTRA OF PULSE INCLUDING SEVERAL BUBBLES (continued)

8-lb TNT

Shot No.	Range (ft)	Octave Bands 15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
43	1,059	43.65	685.2	418.8	508.1	423.3	384.4	274.6	149.8	96.50	78.93
69	1,067	33.89	816.0	465.3	576.2	419.4	374.6	264.8	141.8	90.74	50.08
21	1,701	6.587	130.1	319.3	209.8	165.2	131.1	93.40	43.59	19.77	7.089
35	1,854	2.890	74.70	279.0	142.7	124.6	108.5	76.36	40.76	20.01	9.820
4	1,871	8.143	97.86	282.7	170.6	150.1	130.8	69.57	40.16	19.77	8.790
47	2,743	1.207	12.19	123.0	61.61	61.83	42.36	27.48	14.48	6.293	2.282
32	4,130	--	1.283	25.93	45.57	28.49	20.09	11.88	5.468	2.182	0.6974
25	4,200	--	1.[illegible]39	28.52	50.63	30.21	20.27	11.52	5.200	2.053	0.4179
55	4,362	--	1.588	26.92	49.07	30.22	19.89	10.09	5.238	2.544	1.179
18	13,119	--	--	0.07169	1.039	5.158	1.872	0.7354	0.3014	0.1182	0.03905
36	13,222	--	--	0.09460	1.071	6.455	2.397	1.352	0.1627	0.1879	0.05728

8-lb HBX-3

Shot No.	Range (ft)	15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
44	1,000	271.4	1047.	704.4	457.2	399.6	350.5	274.3	156.0	99.11	86.89
11	1,178	77.91	634.0	423.5	302.4	245.4	245.6	174.3	92.73	54.20	30.73
50	4,022	--	3.934	64.98	23.37	19.19	15.65	12.12	5.694	2.672	1.146
71	9,665	--	--	0.8871	15.52	5.108	3.152	2.214	1.053	0.5600	0.2715
75	13,360	--	--	0.1385	3.228	5.966	2.135	0.8574	0.4420	0.1832	0.05301

TABLE 4

SPECTRA OF PULSE INCLUDING SEVERAL BUBBLES (continued)

57-lb TNT

Shot No.	Range (ft)	Octave Bands 15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
8	1,660	541.3	2043.	1491.	1341.	1012.	906.0	377.6	176.5	92.90	33.82
29	1,744	523.2	2042.	1567.	1010.	850.6	514.2	415.5	191.7	94.11	43.31
37	4,102	10.04	123.5	410.4	198.6	157.0	85.79	43.69	21.09	7.780	1.816
20	4,251	5.954	116.6	380.0	208.3	158.8	91.98	49.97	24.33	10.78	5.735
3	6,428	1.092	10.41	141.5	94.73	58.53	36.00	14.91	7.433	3.770	1.500
79	6,967	1.085	12.59	163.6	103.6	62.93	40.21	16.27	7.394	4.549	2.619
62	14,162	--	0.3849	5.309	37.64	14.47	8.615	3.447	1.441	0.8080	0.4317

50-lb HBX-3

Shot No.	Range (ft)	15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
63	1,626	2411.	2406.	1558.	1158.	1045.	786.2	494.5	209.4	107.1	37.19
78	2,760	200.3	1153.	577.8	365.5	325.0	267.1	145.5	73.13	50.18	37.76
53	4,259	16.34	328.3	328.3	142.8	121.7	101.0	45.91	23.64	14.43	8.836
57	7,326	1.303	14.72	153.2	44.05	35.30	18.90	10.98	5.207	2.733	1.369
59	9,419	--	1.529	38.98	19.29	9.856	6.634	3.693	1.680	0.7933	0.4035

TABLE 4

SPECTRA OF PULSE INCLUDING SEVERAL BUBBLES (continued)

88-lb Nitramex

Shot No.	Range (ft)	Octave Bands									
		15-30cps	30-60	60-125	125-250	250-500	500-1000	1-2kcs	2-4	4-8	8-16
38	2,610	177.0	1153.	662.2	448.8	329.1	226.5	127.1	75.57	65.22	30.71
19	2,751	139.2	698.5	395.5	337.2	239.5	193.5	77.08	39.68	20.10	6.189
39	6,864	0.4785	8.782	114.7	53.34	32.55	24.04	10.41	5.646	3.843	2.032
40	10,122	--	1.696	34.58	44.88	18.44	10.14	4.861	2.698	1.591	1.118

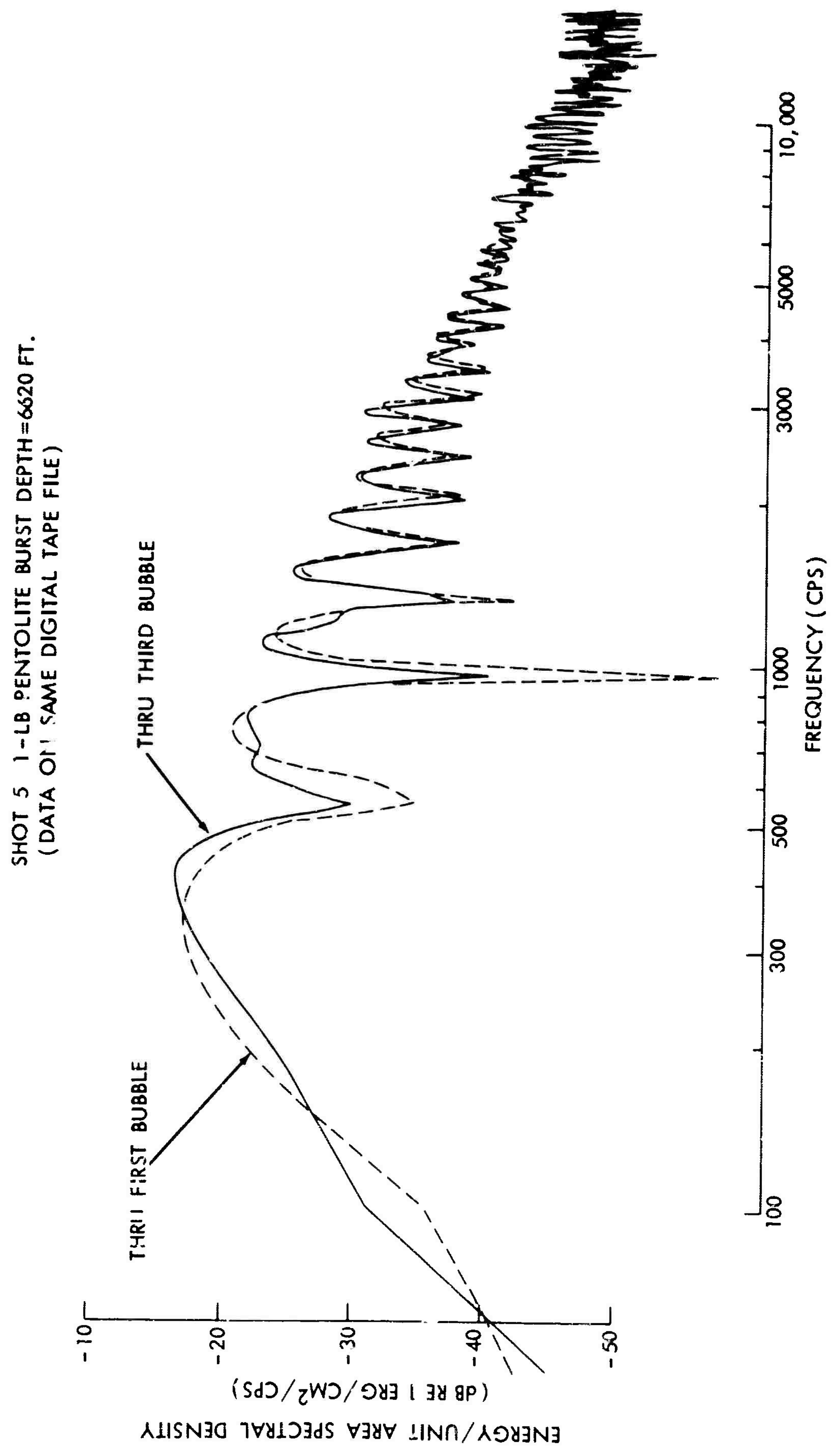

FIG. 1 EFFECT OF NUMBER OF BUBBLES INTEGRATED UPON ENERGY SPECTRUM

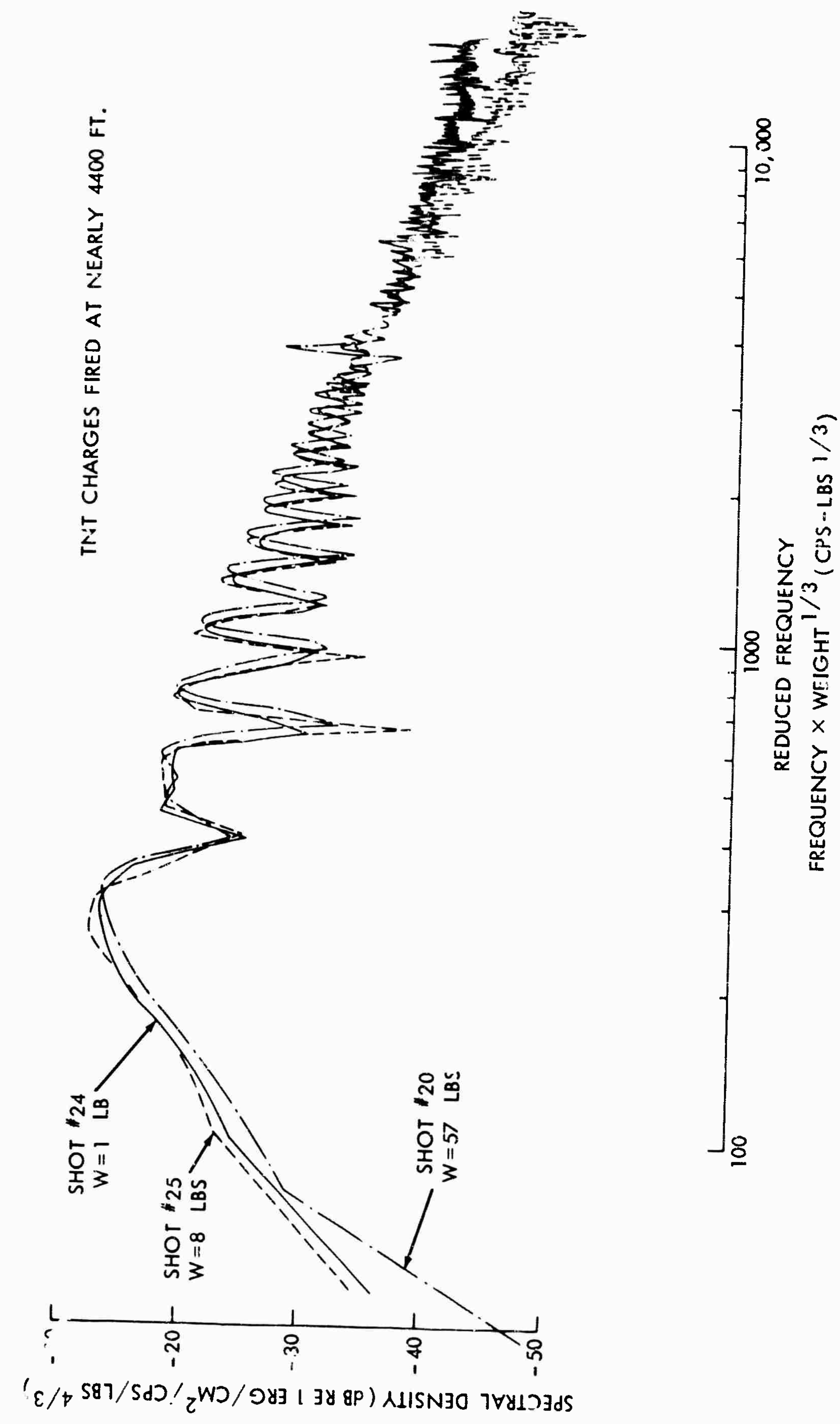

FIG. 2 EFFECT OF CHARGE WEIGHT ON ENERGY SPECTRUM

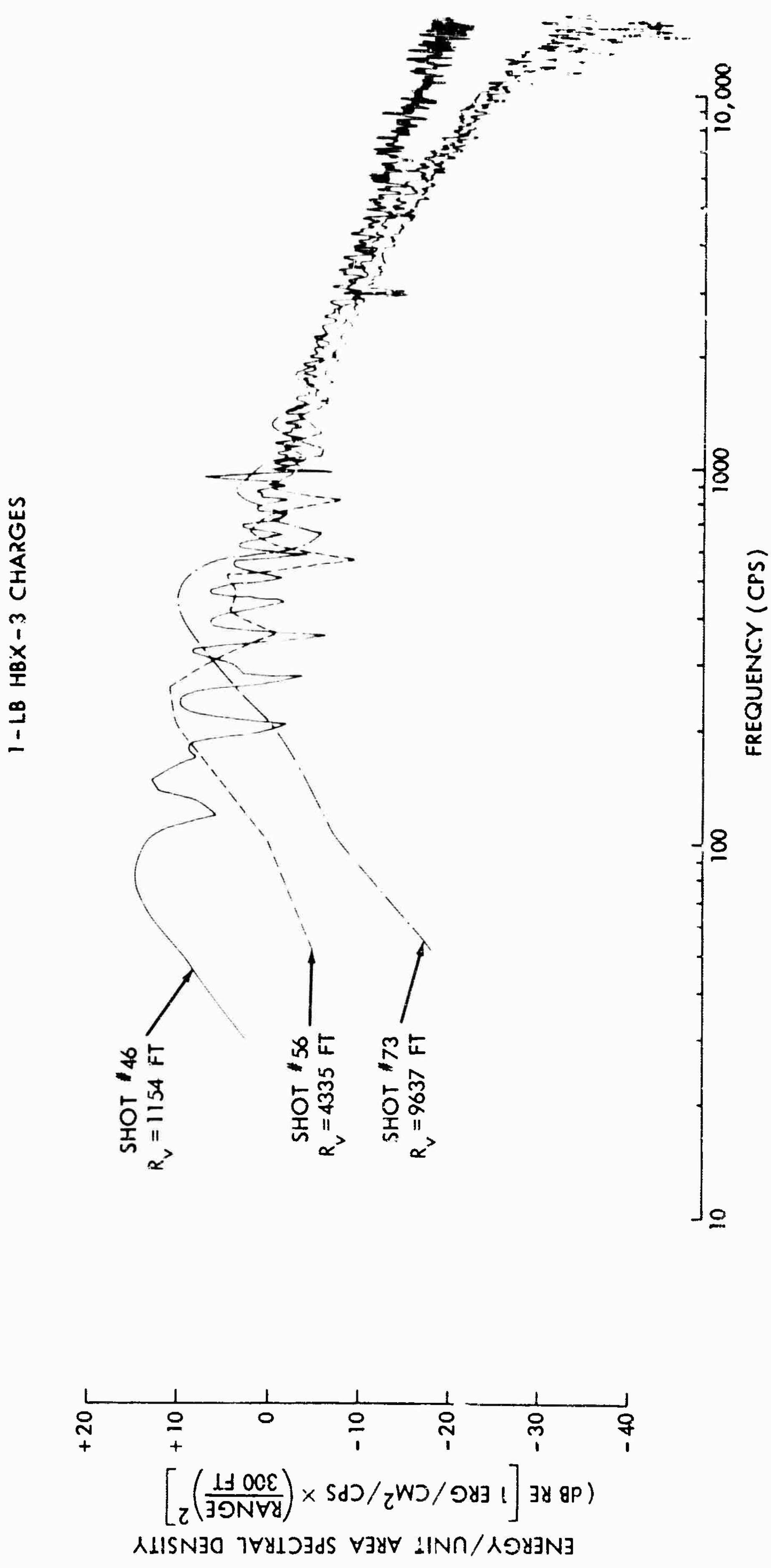

FIG. 3 EFFECT OF RANGE-DEPTH UPON ENERGY SPECTRUM

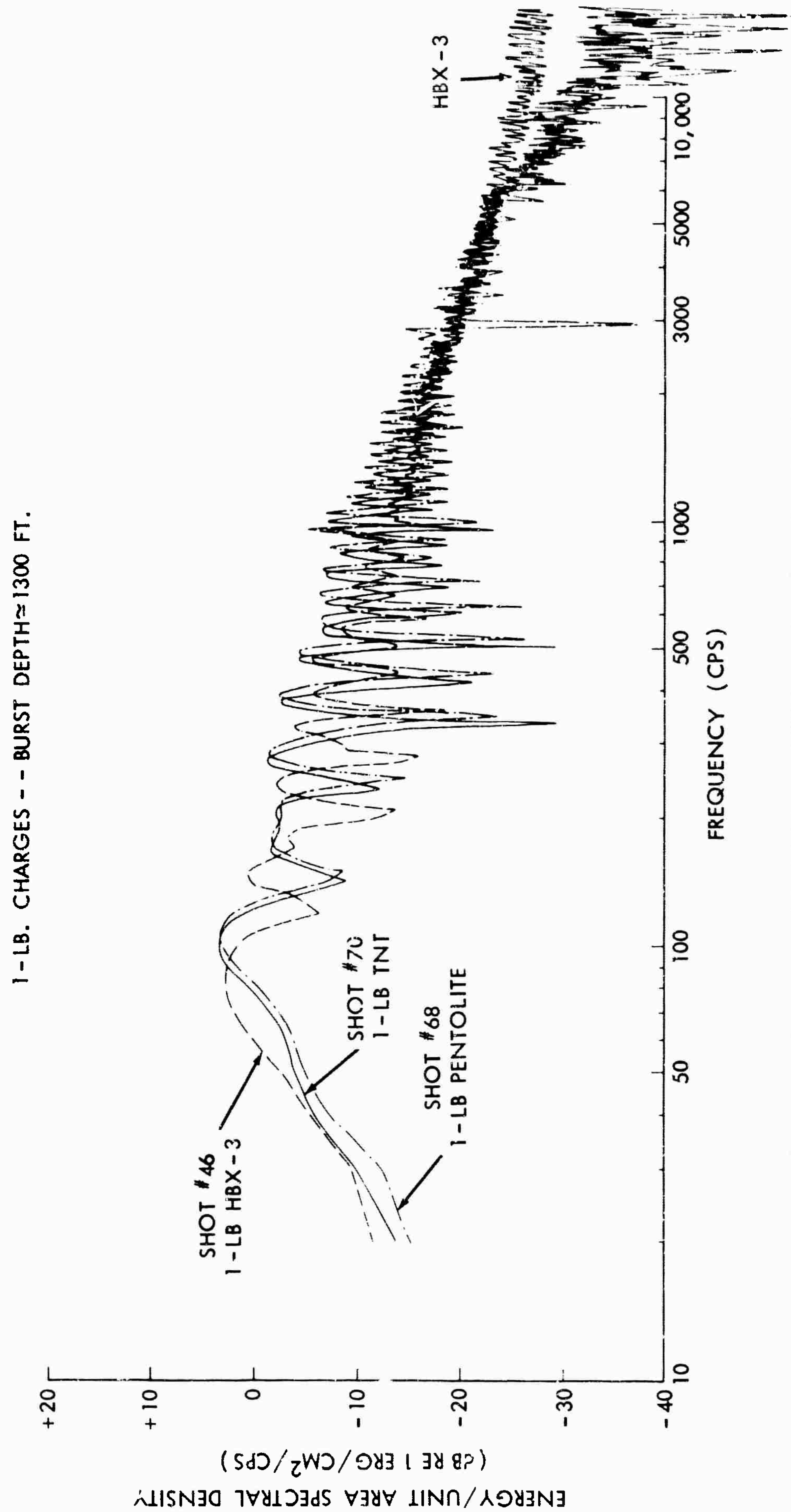

FIG. 4 EFFECT OF CHARGE COMPOSITION UPON ENERGY SPECTRUM

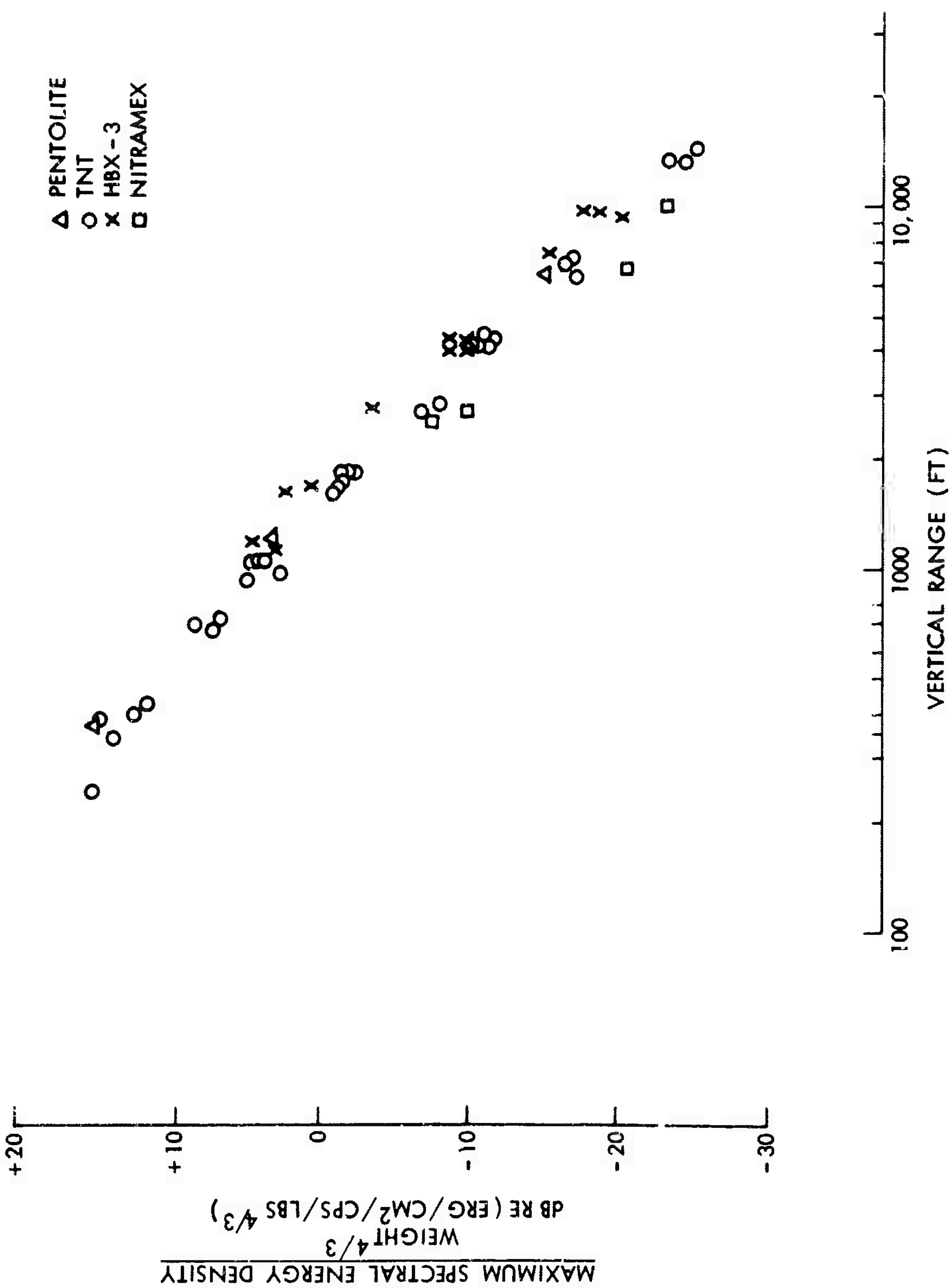

FIG. 5 TOTAL PULSE MAXIMUM SPECTRAL ENERGY DENSITY

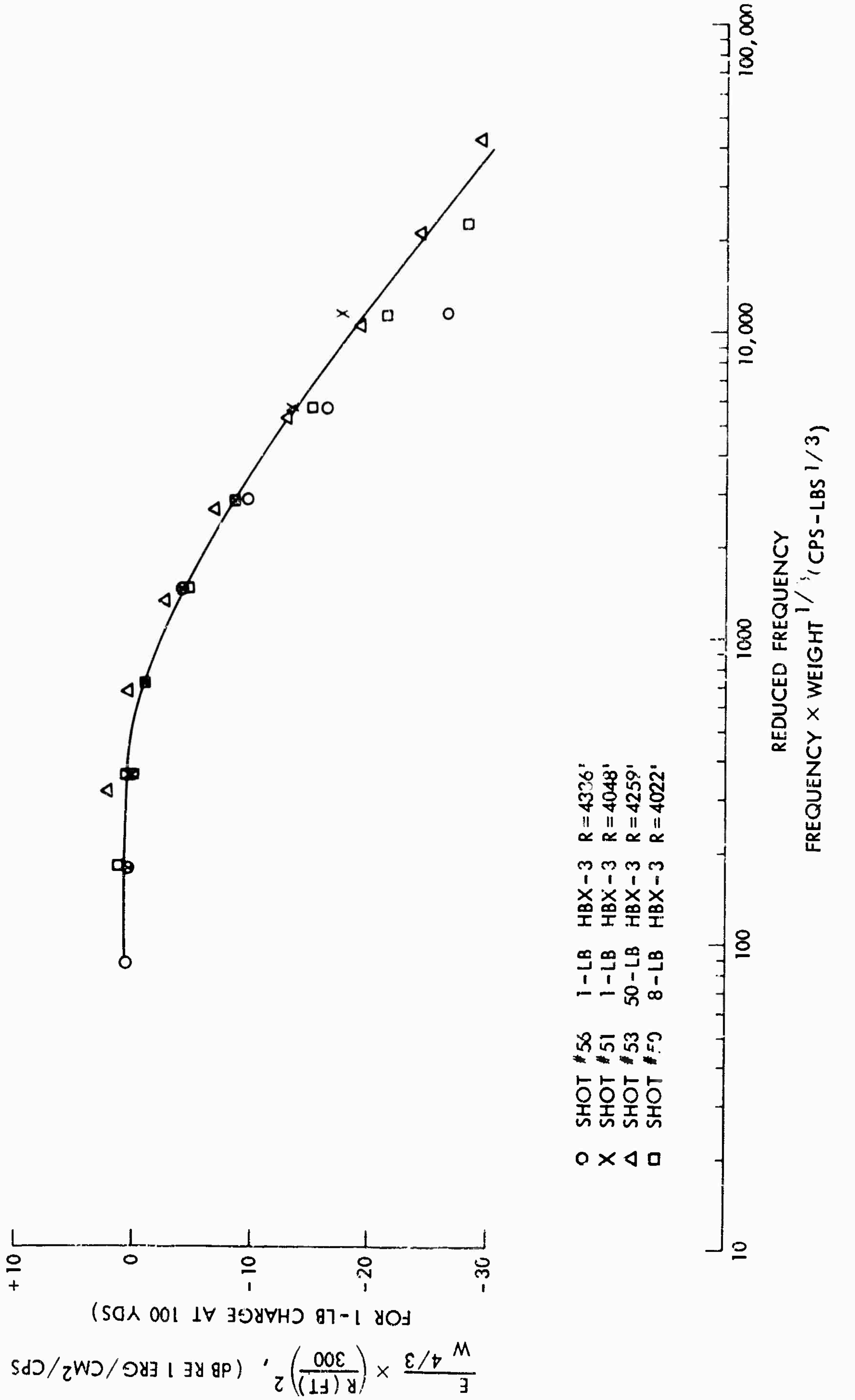

FIG. 6 SHOCK WAVE OCTAVE BAND ENERGY FOR HBX-3 CHAR

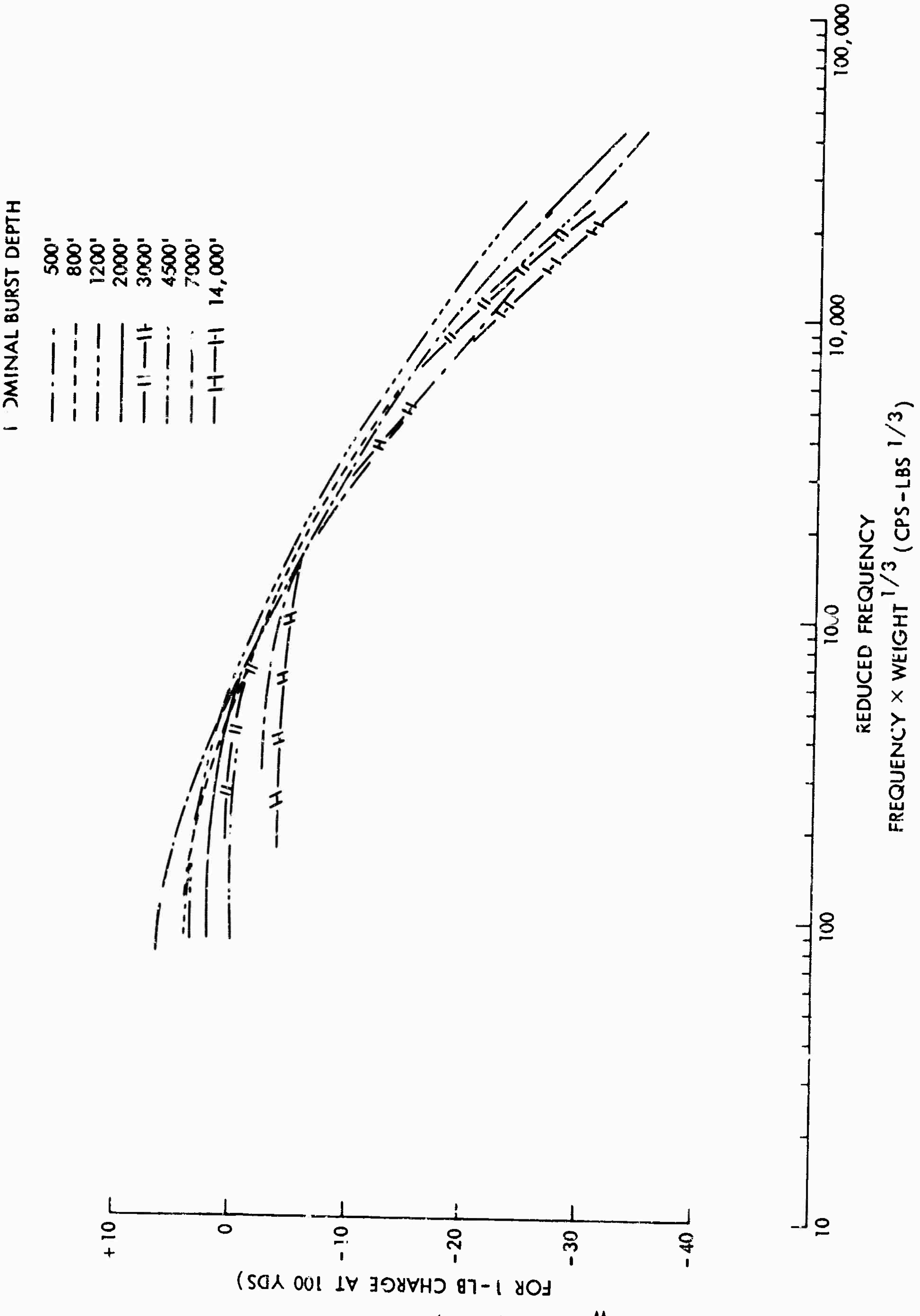

FIG. 7 SHOCK WAVE OCTAVE BAND ENERGY FOR TNT CHARGES

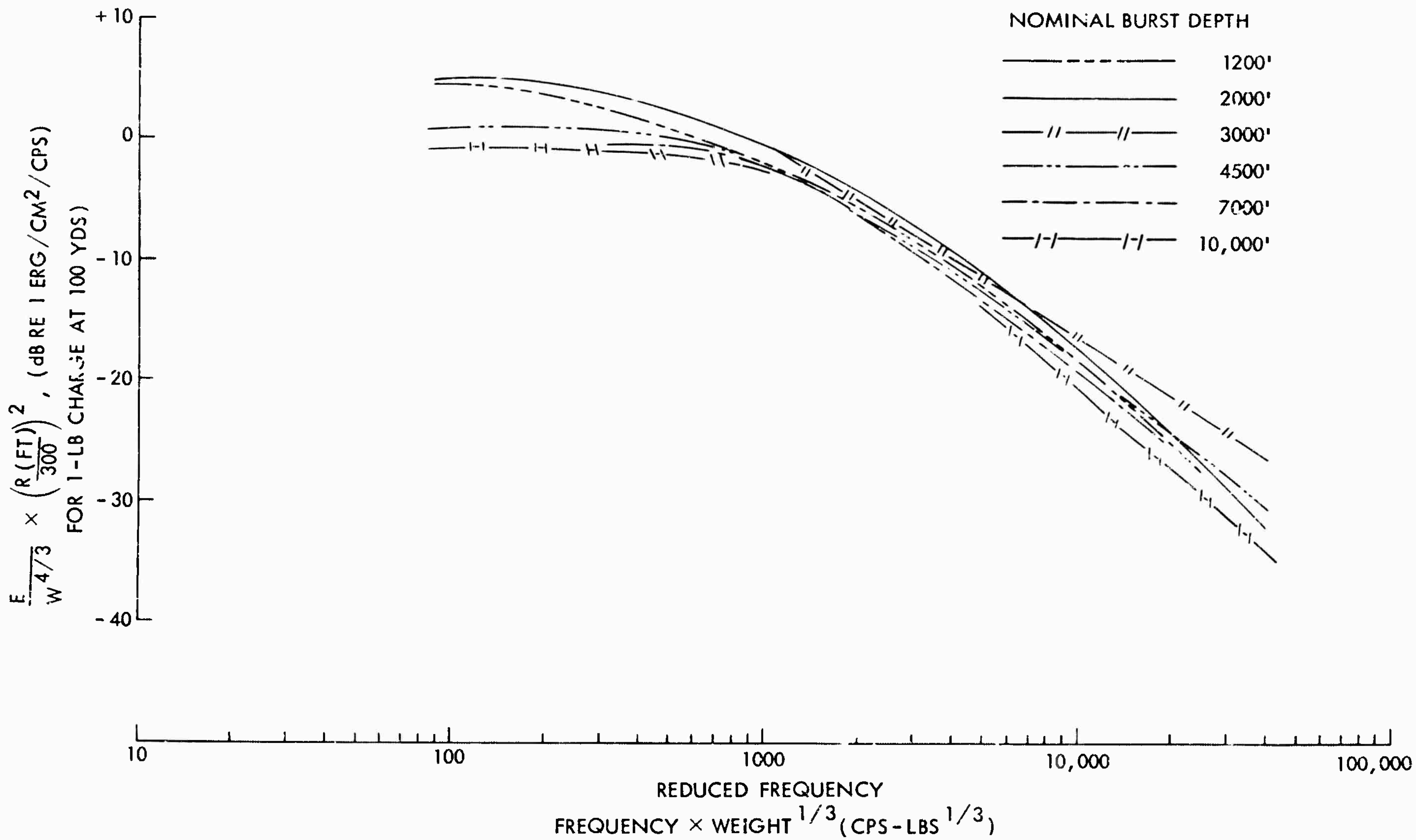

FIG. 8 SHOCK WAVE OCTAVE BAND ENERGY FOR HBX-3 CHARGES

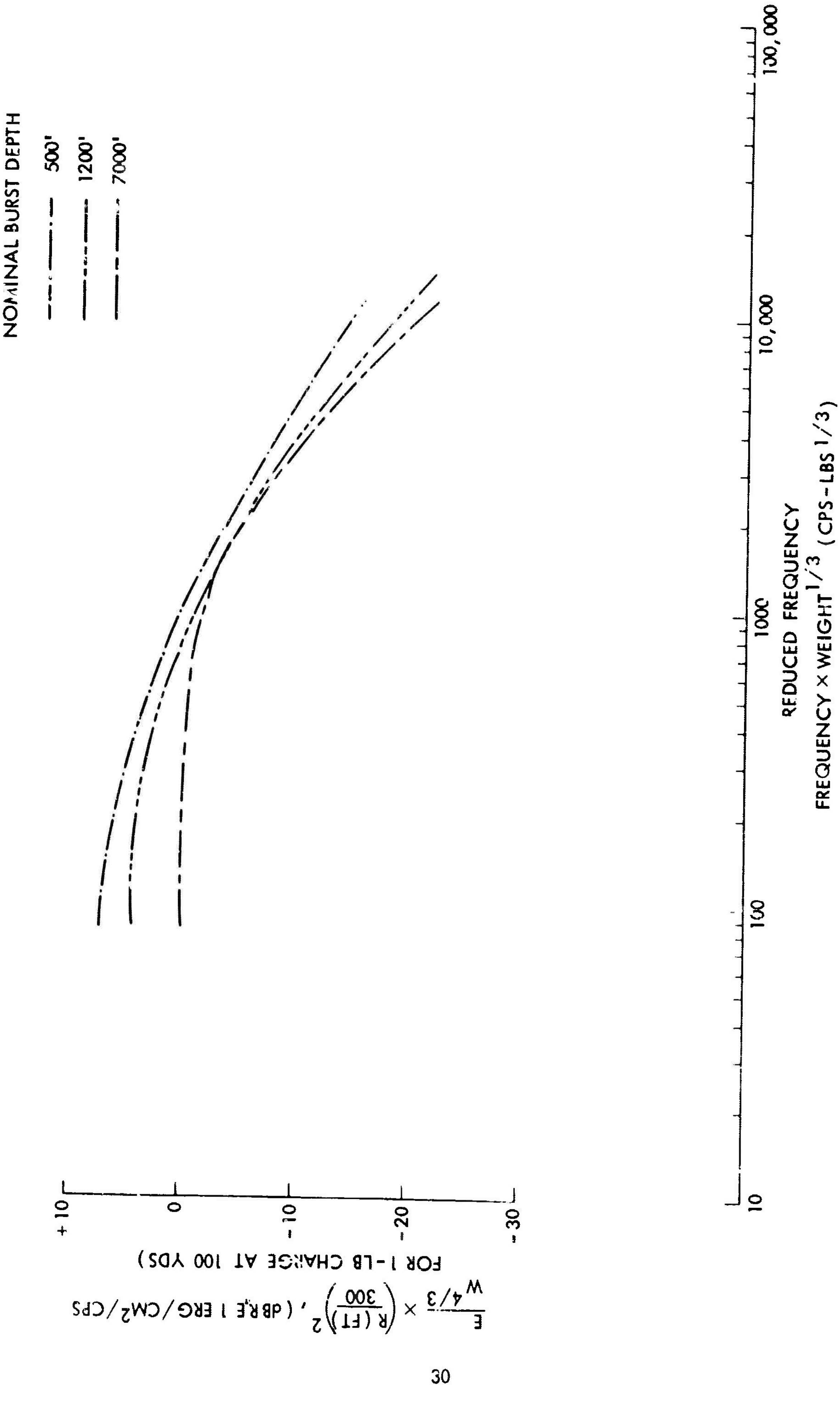

FIG. 9 SHOCK WAVE OCTAVE BAND ENERGY FOR PENTOLITE CHARGES

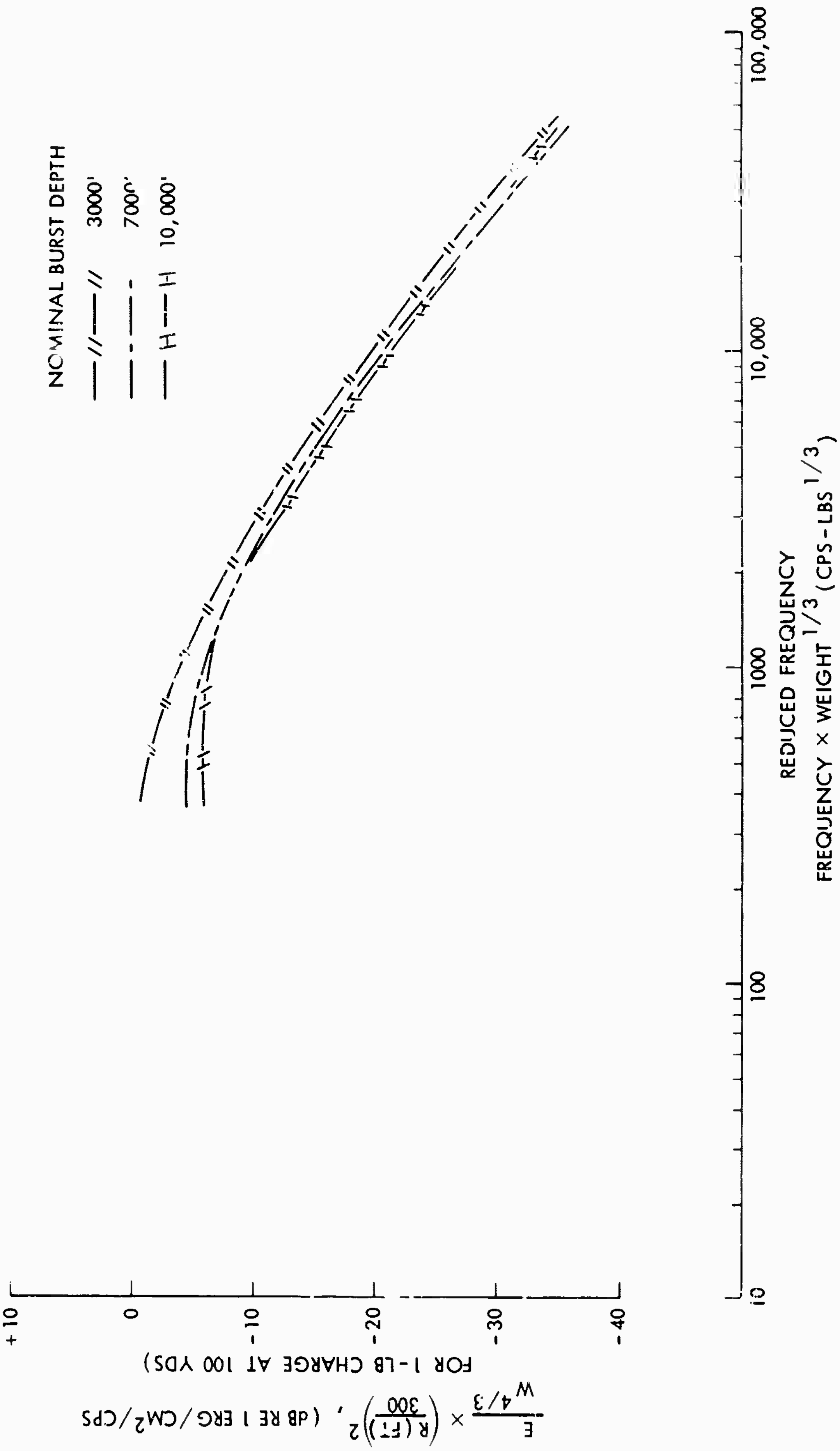

FIG. 10 SHOCK WAVE OCTAVE BAND ENERGY FOR NITRAMEX CHARGES

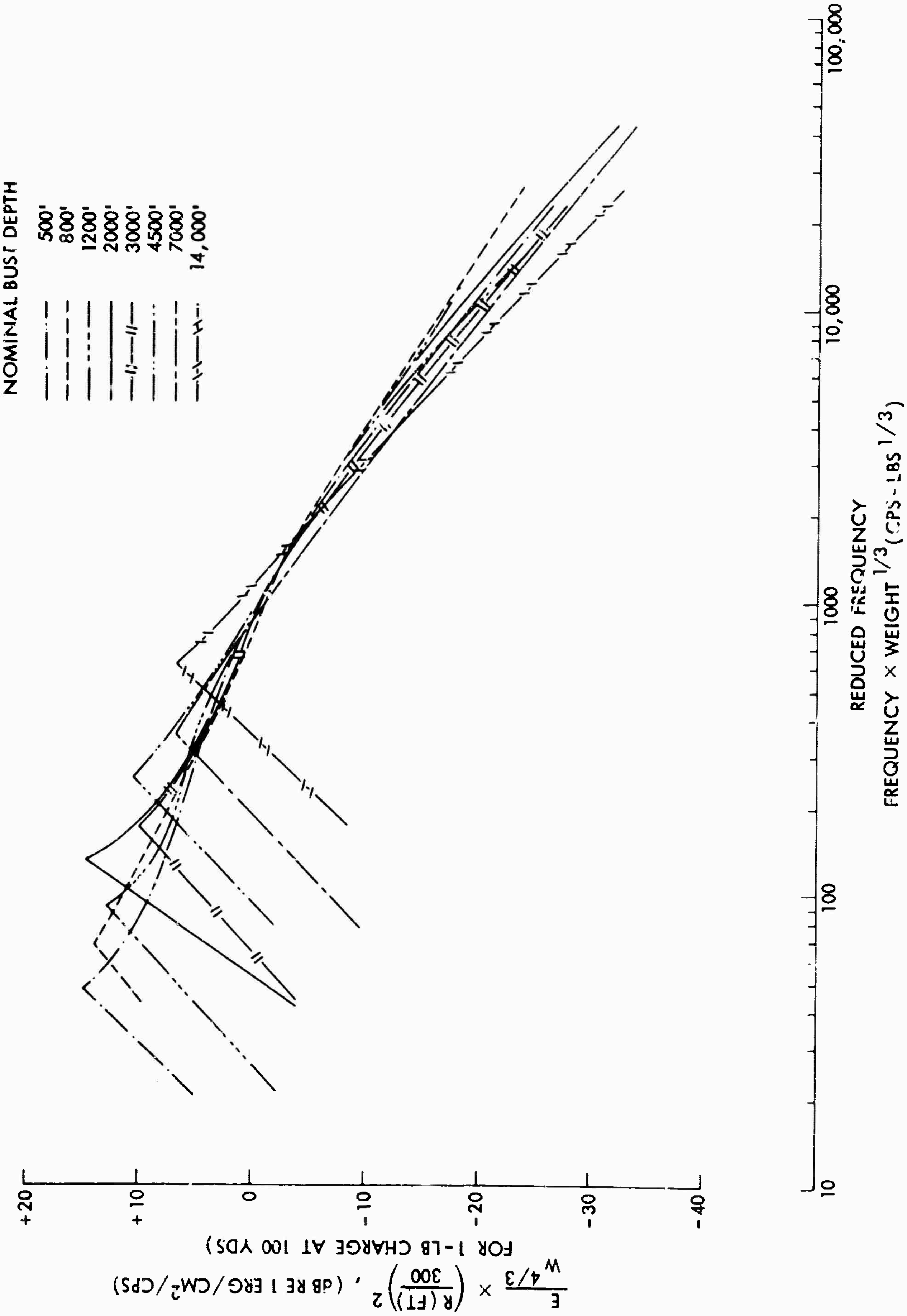

FIG. 11 TOTAL PULSE OCTAVE BAND ENERGY FOR TNT CHARGES

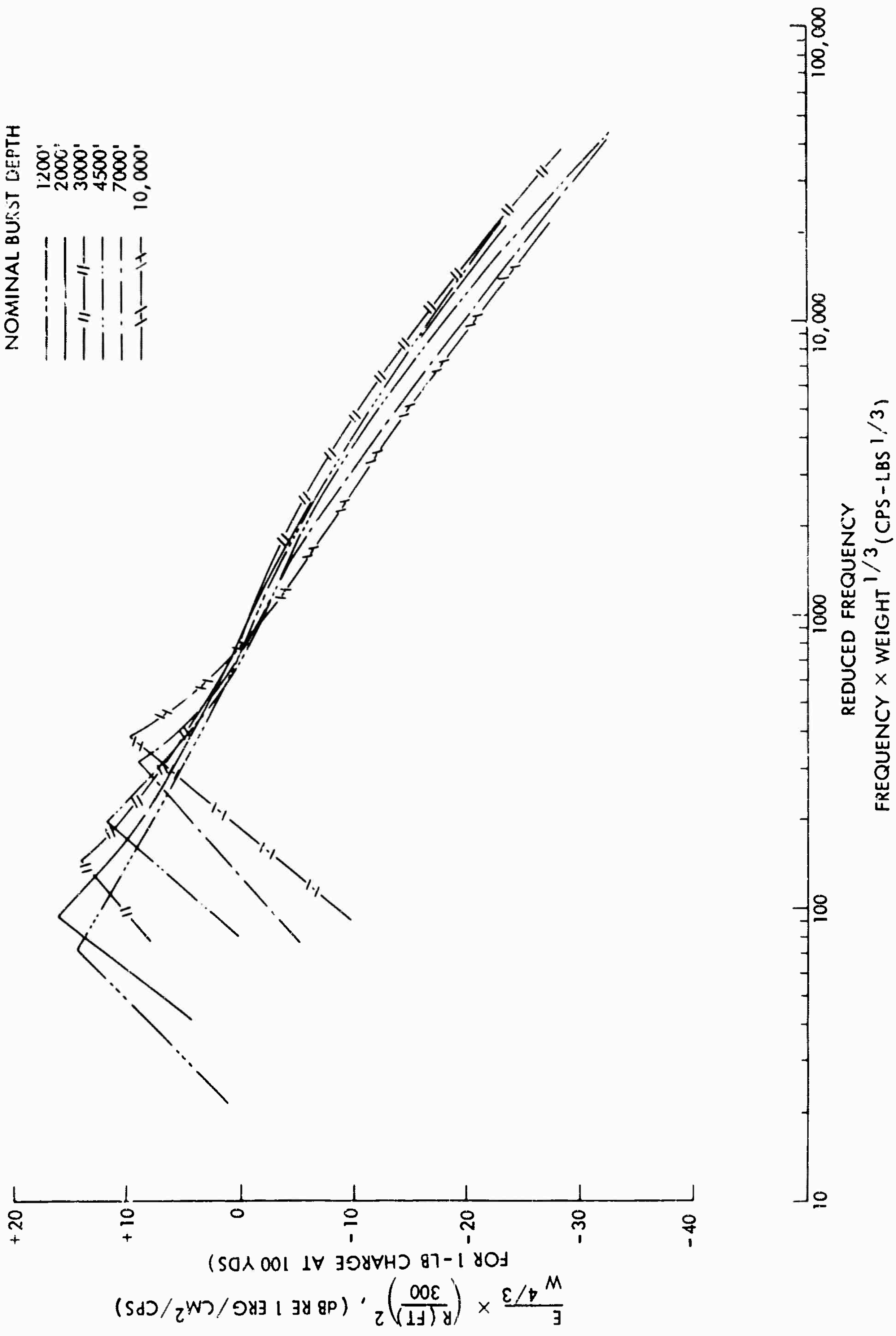

FIG. 12 TOTAL PULSE OCTAVE BAND ENERGY FOR HBX-3 CHARGES

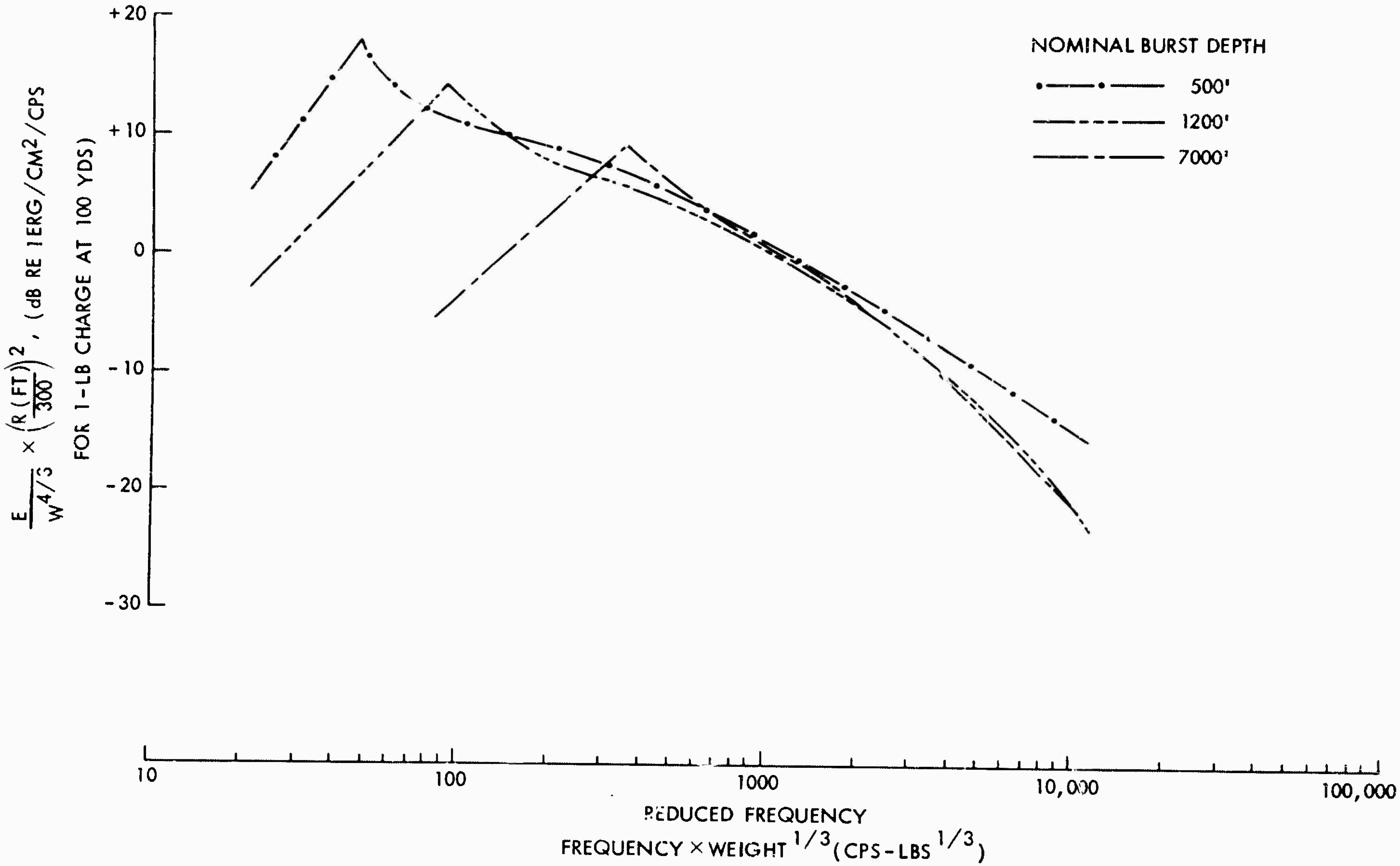

FIG. 13 TOTAL PULSE OCTAVE BAND ENERGY FOR PENTOLITE CHARGES

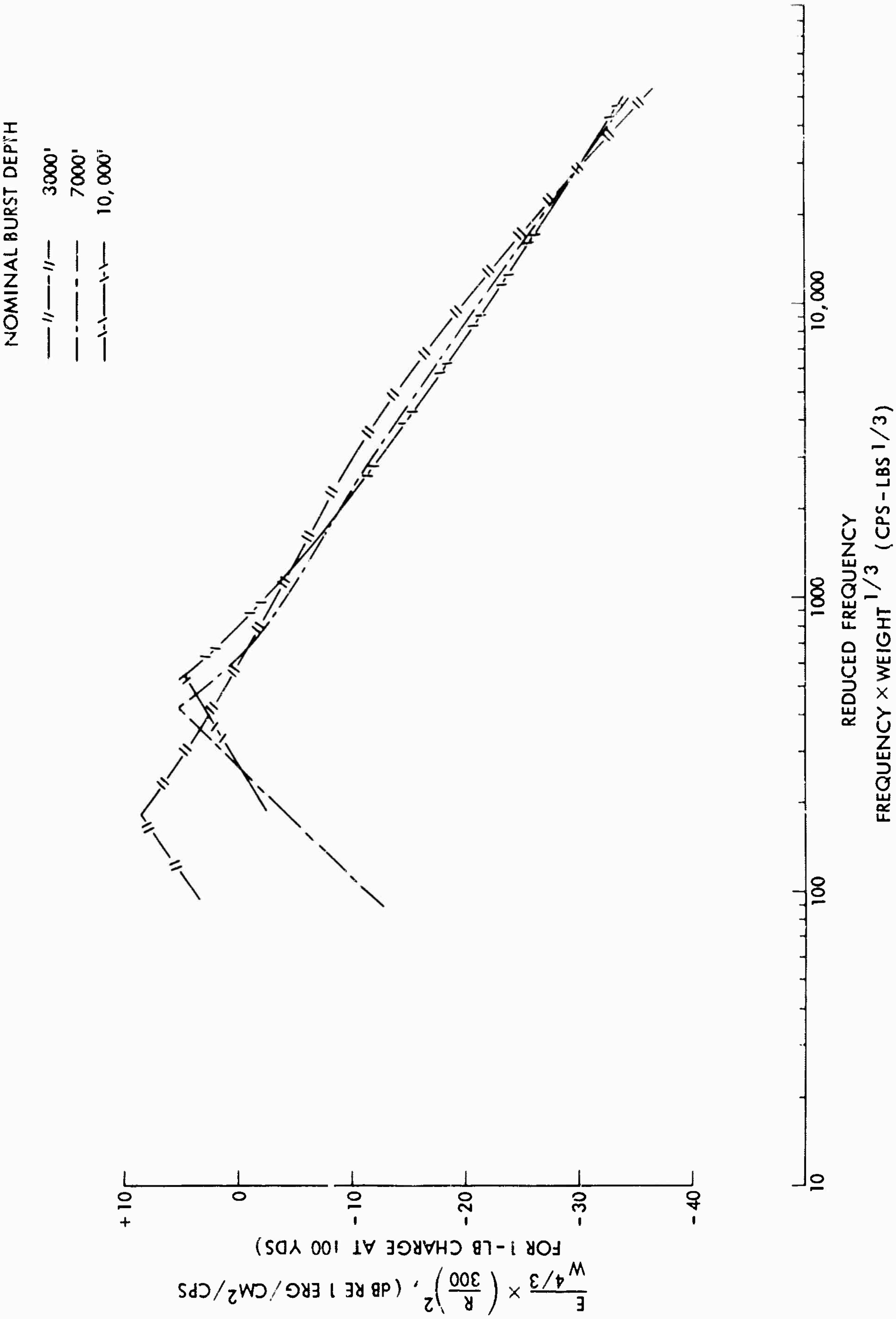

FIG. 14 TOTAL PULSE OCTAVE BAND ENERGY FOR NITRAMEX CHARGES

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APPENDIX A

REPRODUCIBILITY OF SPECTRA FROM DIGITIZED DATA

In order to test the DTMB Computer Data Format Translator with our analog tapes, repeat runs of digitization were made and the results compared. This was done for a record which was analyzed only for the positive shock wave pulse, and for another record analyzed through the first bubble pulse.

Figure A-1 illustrates typical energy spectra of the positive phase of the shock wave. The two plots shown are of the same shot, No. 46, a 1-lb HBX-3 charge fired at 1330 feet, the difference being that the analog data was digitized on different days. This was done to check the reproducibility of the DTMB equipment. The spectrum becomes level at the lower frequencies and approaches the impulse* at zero frequency. The reproducibility of the shock wave spectra at low and mid frequencies is observed to be quite good.

The spectrum of an exponential pulse should ideally have a -6 dB per octave slope in the high frequencies (reference g). However, in Figure A-1 the slopes of the spectra are -5 dB per octave and -11 dB per octave, respectively. Although the sampling was at 33 μsec intervals in both cases, the sampling was probably initiated at different times, resulting in digitizing different portions of the pressure-time data. In this particular case, where the rise times are the order of 50 μsec, θ** about 150 μsec, and the sampling interval 33.3 μsec, reading different pressures on the rise and near the peak could result in different slopes in the spectrum at the highest frequencies. This was verified by reading the same pressure-time Visicorder record on the Telereadex in such a way that the sampling was controlled by starting the sampling at different times relative to the discontinuous rise of the shock wave. It becomes apparent that the sampling should have been at closer intervals; however, the available 16.6 μsec sampling rate was not used because it introduced too much noise, as mentioned before.

Figure A-2 shows examples of energy spectra of a pulse integrated to the end of the positive phase of the first bubble pulse. Here again the same analog data was digitized twice. As expected for oscillating functions, the maximum energy occurs at the oscillating frequency; i.e., at the bubble period frequency (35 cps) and then continues to oscillate at integral multiples of this frequency. At 500 cps, the interval in which the spectrum was computed was changed from 5 to 50 cps; therefore,

---

* Impulse is defined as $\int_0^T p(t)dt$, where T is the duration of the pressure pulse, p(t), being integrated.

** θ, the time constant of the pressure pulse, is defined as the time where the pressure falls to 1/e of its maximum value, p_m.

the 35 cps oscillations are not well defined for frequencies greater than 500 cps. It is apparent that the spectra are in good agreement from the bubble fundamental frequency to about 6-8 kcs. In the high frequencies, the slight differences in slope are again attributed to the relatively coarse sampling rate and the uncontrolled starting point of the sampling.

Although the characteristics of the two curves from about 20 cycles to about 5 cycles are similar, the discrepancies are 3 to 5 dB. This large discrepancy is probably due to the different baselines calculated, since a slight shift in the baseline could produce relatively large differences in the impulse.

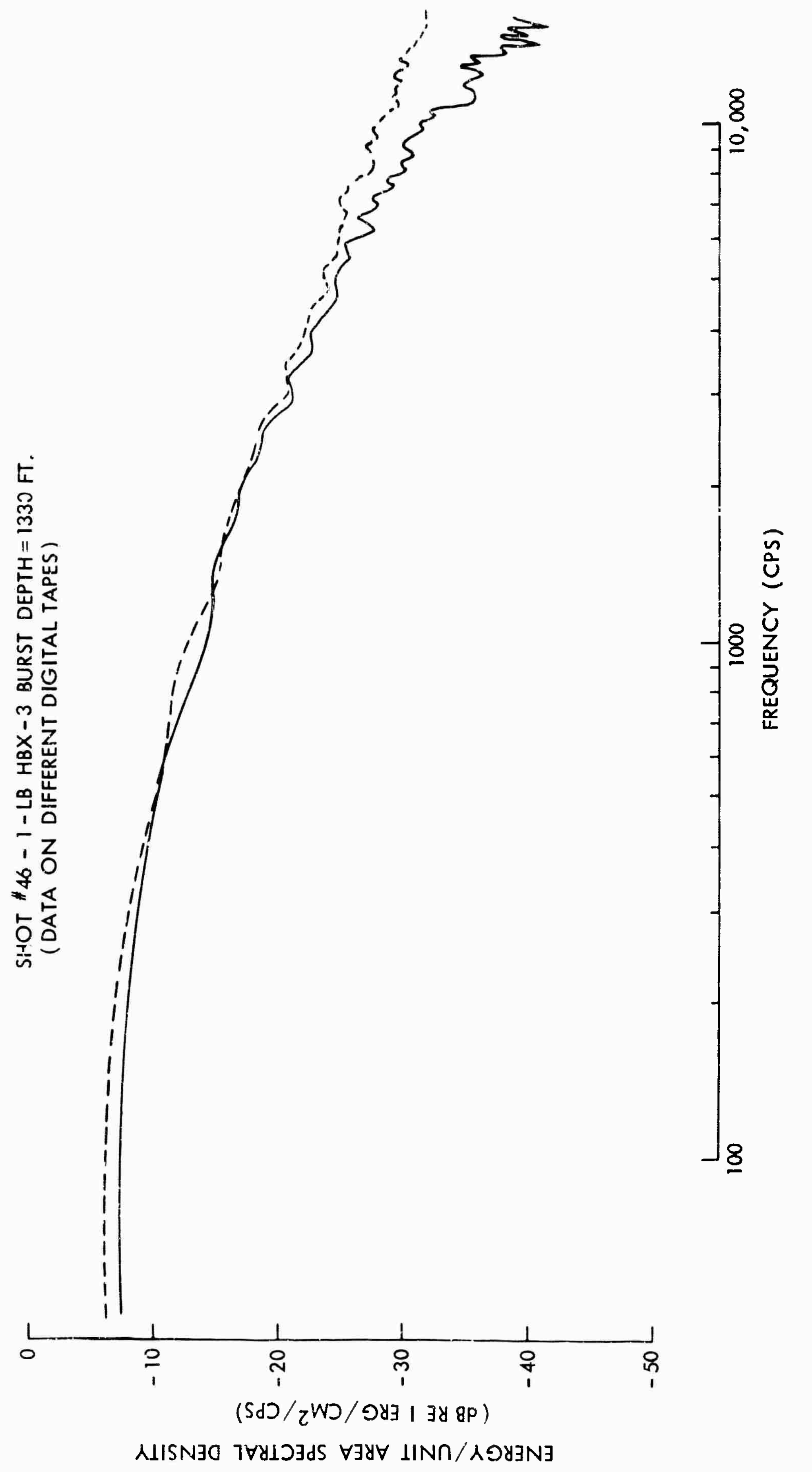

FIG. A-1 REPRODUCIBILITY OF SHOCK WAVE SPECTRUM

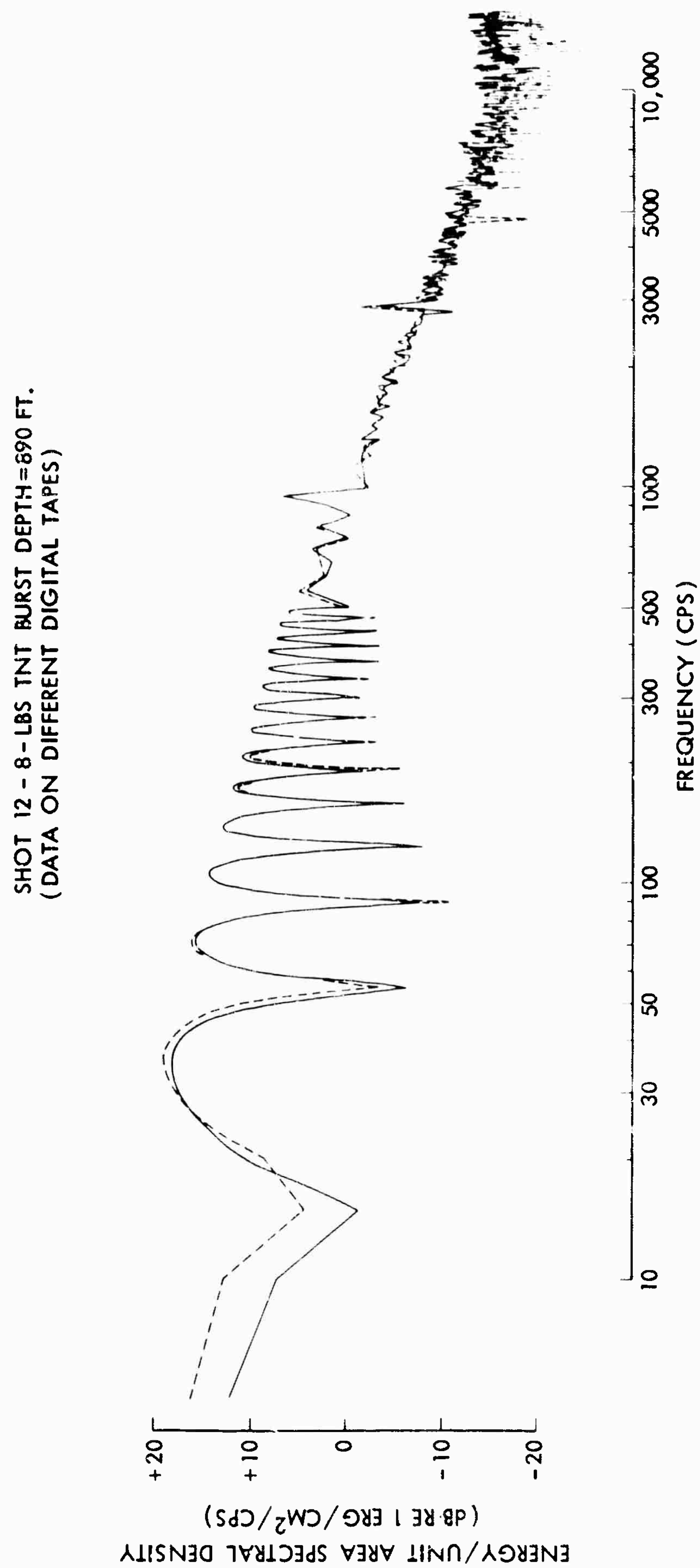

FIG. A-2 REPRODUCIBILITY OF TOTAL PULSE SPECTRUM

Unclassified
Security Classification

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13. ABSTRACT

Fourier spectra were computed on the IBM 7090 for analog tape recorded pressure pulses of underwater explosions fired at sea in February 1965. Depths ranged from 500 to 14,000 feet; charges weighed 1 to 88 pounds; the compositions fired were TNT, pentolite, HBX-3, and Nitramex. Reduced spectra of charges weighing up to 57 pounds agreed with previous results from 1 and 10 pound charges at the same depths. Only slight differences due to composition were found.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Un' rwater 'xplosion						
Sho' Waves						
Frequency Spe trum						
'nderwater Sound						
Bubble P lses						
TNT						
HBX-3						
Pentolite						
Nitramex						